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Materials Engineering and Research Office Report**



**Performance of Electric Arc
Furnace Steel Slag
in Ontario Low-Volume Roads**

MERO-011

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Abstract	In 1991, both steel slag and blast furnace slag coarse and fine aggregate were banned for use in any hot mix asphalt for ministry work because of reduced pavement life. One alternate possibility of using large volumes of steel slag was to find a less harmful engineered application in the roadbed. This report documents the experimental use of electric arc furnace (EAF) steel slag from eastern Ontario in municipal low-volume road granular base and sub-base applications. Five EAF steel slag test sections were constructed using natural aggregate and EAF steel slag base and sub-base combinations. Annual inspection of the test sections, trench sampling, and laboratory testing of the steel slag were conducted from 1991 to 2002. The objective of this experiment was to document the long-term expansion characteristics and field performance of EAF steel slag in the test sections. This long-term experiment provided engineering data that indicate that fresh EAF steel slag, when used in the same manner as natural aggregate, can be used successfully in low-volume road applications. Special care must be taken in choosing the most appropriate application to mitigate problems arising from inherent variable chemical composition and the unknown amount of expansion potential remaining in the material. Ministry of Transportation use of this material would not be practical, due to the fact that high-volume provincial highways need to be paved as quickly as possible, unless suppliers establish stockpiles that have been allowed to achieve an acceptable level of expansion. Considerations for granular base and sub-base low-volume road applications are given in the report.
Key Words	aggregate; steel slag; electric arc furnace slag; granular base; granular sub-base; pavement; low-volume roads; Ontario
Distribution	Unrestricted technical audience



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Executive Summary

In 1991, both steel slag and blast furnace slag coarse and fine aggregate were banned for use in any hot mix asphalt for ministry work. This action was taken as a result of premature deterioration of premium quality asphalt pavements containing steel slag aggregates. The ban on steel slag use resulted in an unfortunate situation for both the ministry and the slag suppliers. The ministry lost an opportunity to accept steel slags on ministry contracts within the concept of 3R (Reduce, Reuse, Recycle). Steel slag producers lost their opportunity to market steel slag aggregate in competition with premium quality natural aggregates. One alternate possibility of using large volumes of steel slag was to find a less harmful engineered application in the roadbed.

This report documents the experimental use of electric arc furnace (EAF) steel slag from eastern Ontario in municipal low-volume road granular base and sub-base applications. Five EAF steel slag test sections were constructed using natural aggregate and EAF steel slag base and sub-base combinations. Annual inspection of the test sections, trench sampling, and laboratory testing of the steel slag were conducted from 1991 to 2002. The objective of this experiment was to document the long-term expansion characteristics and field performance of EAF steel slag in the test sections.

This long-term experiment provided engineering data that indicate that fresh EAF steel slag, when used in the same manner as natural aggregate, can be used successfully in low-volume road applications. Special care must be taken in choosing the most appropriate application to mitigate problems arising from inherent variable chemical composition and the unknown amount of expansion potential remaining in the material.

Ministry of Transportation, Ontario (MTO) use of this material would not be practical, due to the fact that high-volume provincial highways need to be paved as quickly as possible, unless suppliers establish stockpiles that have been allowed to achieve an acceptable level of expansion. Considerations for granular base and sub-base low-volume road applications are given in the report.

EAF steel slag is not recommended for ministry use. Slags that are known to be even more expansive are also not recommended for ministry work. Chemical material variability and unpredictable expansion behaviour are the prime concerns. Appropriate quality control measures and treatment by the Ontario steel-making industry would be required to improve engineering and environmental quality of this material before ministry use could be considered. Technology and quality management systems to overcome these problems exist and have been utilized in western Europe and the United States.

Introduction

Three kinds of steel or iron slags are available in Ontario. Blast furnace (BF) slag is produced when iron ore is melted in the blast furnace to produce iron. Further processing of iron or scrap metal, using fluxing agents such as lime to produce steel in a basic oxygen furnace (BOF) or electric arc furnace (EAF), results in the production of BOF steel slag or EAF steel slag, respectively. More expansive ladle slags may also be generated during the final refining stage of steel making. This report documents the experimental use of fresh EAF steel slag from eastern Ontario in municipal low-volume road granular base and sub-base applications.

Ministry involvement with steel slag use as aggregate dates back to 1974 when the first asphalt surface course steel slag test section was built on Highway 401 on contract 74-20 [Ryell *et al*, 1979]. Steel slag aggregate delivery and use in surface course applications as HL1 coarse aggregate and Dense Friction Course (DFC) coarse and fine aggregate started in the 1980 construction season. In 1986, serious early performance problems began to be noticed with the steel slag aggregate DFC pavements. In the mid to late 1980s and early 1990s, the ministry investigated many steel slag DFC pavements that were performing inadequately [Rogers, 1994].

EAF steel slag from the L'Original steel works of Ivaco Rolling Mills was first placed in a HL1 test section on Highway 417 on contract 83-09. It was subsequently approved for use in HL1 and DFC applications. It was used on two contracts (87-16 and 89-81) as HL1 steel slag coarse aggregate. Total tonnage used including the test section was approximately 17,730 tonnes.

In 1991, both steel slag and blast furnace slag coarse and fine aggregate were banned for use in any hot mix asphalt for ministry work. This action was taken as a result of premature deterioration of premium quality hot mix pavements containing steel slag aggregates.

Steel slag has a variable chemical composition and can contain oxides of calcium (CaO) and magnesium (MgO). The hydration of these oxides and accompanying expansion in steel slag has been found to be one of the contributing factors of this complex and costly materials-engineering problem. The problem of steel slag expansion is not a new one and it is a well-recognized phenomenon. The first documented case of damage in Ontario, to a building located at the Canadian end of the international bridge between Michigan and Ontario at Sault Ste. Marie, due to the use of steel slag from a local steel mill, was reported in 1969 [Crawford and Burn, 1969].

The ban on steel slag use resulted in an unfortunate situation for both the ministry and the slag suppliers. The ministry lost an opportunity to accept steel slags on ministry contracts within the concept of 3R (Reduce, Reuse, Recycle) due to engineering reasons. Increased costs of repair, reconstruction, and disposal had to be absorbed by the ministry due to

reduced pavement life, mostly in southern Ontario. Steel slag producers lost their opportunity to market steel slag aggregate in competition with premium quality natural aggregates.

One alternate possibility of using large volumes of steel slag was to find a less harmful engineered application in the roadbed. Fresh steel slag could be processed to meet the specification requirements of natural aggregate Granular Base Course A (GBC A) and Granular Sub-Base Course B (GBC B) using conventional aggregate processing technology. The only remaining unknowns were documented long-term field performance of steel slag in granular base and sub-base applications, and a specification limit to address tolerable levels of expansion of steel slag.

The purpose of this study was to explore alternate use opportunities of EAF steel slag in road applications other than binder and surface course hot mix aggregates. The local availability of EAF steel slag made possible the experimental use of this material in the vicinity of the Town of Hawkesbury near the Ontario-Quebec border. The objective of this experiment was to document the long-term expansion characteristics and field performance of EAF steel slag in low-volume roads. Five EAF steel slag test sections were constructed using natural aggregate and steel slag base and sub-base combinations. Each test section is described in detail in the body of the report. Annual inspection of the test sections, trench sampling, and laboratory testing of the steel slag were conducted from 1991 to 2002.

Material and Testing

Ivaco Rolling Mills steel works is located in the former Village of L'Orignal, now part of the amalgamated Township of Champlain. This operation recycles scrap steel in an electric arc furnace and was the supplier of EAF steel slag. International Mill Services (IMS) was a company that operated a steel slag aggregate-processing plant associated with the steel works. EAF steel slag was processed in this plant, meeting specification requirements of GBC A and GBC B (Figures B-1 and B-2). There was local interest in using steel slag because there is a shortage of naturally occurring sand and gravel deposits in this area. Natural aggregate products can be trucked in from suppliers farther away or supplied from local bedrock quarries. These alternatives tend to be more expensive due to increased crushing and transportation costs. Local municipalities and land developers were interested in using the locally available EAF steel slag to alleviate poor municipal road conditions, particularly during the spring thaw due to the underlying plastic glaciomarine clay. Maintenance and reconstruction of existing municipal roads and new construction of residential subdivision roads were the available opportunities where the experimental EAF test sections could be evaluated.

In a review paper on slag utilization in pavement construction, the basic mechanism of steel slag expansion is explained [Emery, 1982] as follows:

"The calcium and magnesium oxides are not completely combined in steel slags, and there is general agreement in the literature that the hydration of unslaked lime (free CaO) and magnesium oxide (MgO) in contact with moisture is largely responsible for the expansive nature of most steel slags. The unslaked lime hydrates rapidly and can cause large volume changes in a few weeks. Magnesium oxide hydrates more slowly and contributes to the long-term expansion that may take several years to develop in the field, even when old steel slag dumps are being used."

Both the supplier and the purchasers were aware that the fresh EAF steel slag might cause swelling/expansion damage to the roads. The slag supplier, based on previous experience, expected that in-place curing of the steel slag should provide expansion of less than 0.5 percent in less than six months. ASTM D 4792, Standard Test Method for Potential Expansion of Aggregates from Hydration Reactions, was used for testing steel slag aggregate samples in this experiment. Less than 0.5 per cent expansion at seven days in the ASTM D 4792 test method was adopted as the acceptable limit for expansion for the purposes of this experiment. This choice was in accordance with ASTM D 2940, Standard Specification for Graded Aggregate Material for Bases or Sub-bases for Highways or Airports. Section 3.4 states the following:

"Aggregates that contain components subject to hydration, such as steel slags, shall be obtained from sources approved by the engineer on the basis of either a satisfactory performance record, or of aging or other treatment known to reduce potential expansion to a satisfactory level, or of expansion values not greater than 0.50% at seven days when tested in accordance with Test Method D 4792."

The main precaution taken was that the roads where the test sections were would not be paved for a long time, or at least until the expansion dissipated to a tolerable level. Using this material as backfill to structures or culverts was also not allowed. Reasonable material cost, very short haul distances, and the expectation of stronger, more durable roads were the factors making these test sections possible. The five EAF steel slag test sections were built in 1991 and 1992. Environmental approval was obtained from the local Ministry of Environment (MOE) office by IMS in 1991 based on leachate testing of its EAF steel slag prior to construction. All test sections were built according to applicable local municipal low-volume road construction and maintenance specifications in force at the time of construction.

At the time of construction, representative samples of the slag aggregate were taken. The results of testing of these materials are shown in Appendix A, Tables A-1, A-2, and A-3. These tables also show results of testing of samples taken from the roads at periodic intervals following construction.

Test Section Performance

SUMMARY

Field performance observations of the five test sections indicate that EAF steel slag makes a strong road. Washboarding and potholes similar to those in natural aggregate roads were observed (Figures B-15 and B-16). No complaints were received from municipal road superintendents regarding the performance of the documented test sections. However, the road superintendent for the Township of Champlain did point out that the compacted EAF steel slag road surface was hard on the grader. The EAF road surface did not absorb water as much as a natural aggregate surface would. An ice-blade on a grader was worn out after 300 metres of use. He indicated that the only way to maintain a pure steel slag road was by means of scarification before blading. The suggested practical way to accommodate the toughness of the steel slag is to cover it up with a 50 to 100 mm layer of natural aggregate granular base as top dressing. Local climatic conditions may also influence the long-term performance of steel slag roads.

TEST SECTION 1: CHEMIN DE LA BERGERIE ROAD

The first EAF steel slag test section was built in 1991 in a new residential development called Riviera Estate Subdivision as a new road called Chemin De La Bergerie (Figures 1 and 2). This subdivision is located along the shore of the Ottawa River on the north side of Front Road West, immediately west of the intersection of Front Road West and County Road 4 in the Township of Champlain, formerly the Township of West Hawkesbury, in Prescott and Russell County. The test section is approximately 1200 m long (Figures B-3 and B-4). It was built by placing 150 to 200 mm EAF steel slag GBC A on top of 300 to 450 mm natural sandy aggregate GBC B imported from Quebec. Permission was granted to pave this test section in 1996, as expansion test results indicated that the expansion had decreased to 0.49 per cent versus the specification limit of less than 0.5 per cent expansion at seven days in the ASTM D 4792 test. The road was paved in 1997 with a 50 mm lift of HL3 hot mix asphalt. House construction continued over the years. Before and after paving, the road was travelled by heavy equipment to clear new lots and build the houses. Pavement distress observed during 2001 and 2002 on this road included slight to moderate longitudinal meander and pavement edge cracking (Figure B-6). Possible causes of this type of distress include frost action, insufficient bearing support, excessive traffic loading, and poor construction practices. The subdivision owner's driveway was also built using the same EAF steel slag GBC A, and was paved at the same time as the street. It has not been subjected to the construction and residential street traffic, and showed no pavement distress at all in 2002. Taking into consideration that this test section was not paved for six years, and that the EAF steel slag expansion on a sample collected from this road was 0.1 per cent in the year of paving, it is unlikely that EAF steel slag expansion would be a contributing factor to the observed pavement distress. More EAF slag was placed in this subdivision in 1999 as GBC A and GBC B on the extension of Chemin Des Eaux Paisibles (Figure B-5). Minor amounts of calcite (CaCO_3) were observed leaching out of the slag in the drainage ditches at culverts

in this test section. The performance monitoring of the new road base was beyond the scope of this study.

TEST SECTION 2: RAVARY STREET

This test section was built in early 1992 in the Ravary Estate Subdivision and became named as Ravary Street (Figures 1 and 2). This subdivision is located in the northeast part of the former village of L'Orignal, on the south side of Front Road West and south of Bonin Street in the Township of Champlain, in Prescott and Russell County. The test section road is approximately 1500 m long (Figure B-7). It was built by first placing 300 to 450 mm of EAF steel slag GBC B on clay subgrade. This was followed by placement of 200 to 250 mm of EAF steel slag GBC A. In the following years, the Bonin and Davidson Street portions of the subdivision roads were also constructed with EAF steel slag in the same fashion as described above. During initial sampling of the GBC A and B, it became evident that the slag was well compacted (Figures B-9 and B-10). The top layer formed a very strong travelling surface. A backhoe was required to take representative trench samples. Hand digging of the material would have been very difficult and time consuming. Residential construction did not intensify until the late 1990s in this subdivision. Consequently, the slag roads were not subjected to significant heavy traffic. Expansion data for this test section turned out to be more variable than expected. Test results did not appear to follow the gradually decreasing expansion trend found with the Riviera Estate single layer EAF steel slag test section. Expansion values did decrease below one per cent but remained variable, as shown in Table 1. Ravary Street was paved in 1999 with a single lift of 38 mm HL3 hot mix asphalt and an additional 38 mm lift of HL3 in the following year (Figure B-12). Field inspections of the pavement in 2002 showed no pavement distress. Residential construction has intensified in this subdivision in the last two years with increased traffic on the streets. These slag roads were built with proper drainage ditches (Figure B-8). Observed drainage water remained clean. A white powdery substance leaching out of the steel slag was observed in this test section at a culvert and in the ditch at the intersection of Davidson and Bonin Streets. The white substance was sampled and x-ray diffraction analysis confirmed that it was calcite (Figure B-11). This material probably originated from the free lime that is present in the steel slag. It is also referred to in the technical literature as calcareous tufa [Boyer, 1994]. Calcite may be objectionable on aesthetical grounds. It can also clog pavement drains if present in large quantities [Gupta *et al*, 1994].

TEST SECTIONS 3, 4, AND 5: TOWNSHIP OF ALFRED AND PLANTAGENET

Test Sections 3, 4, and 5 were constructed in 1992 using EAF steel slag in the former North Plantagenet Township as part of routine road maintenance activities (Figures 1 and 2). Local residents were complaining that the roads were soft during spring thaw. EAF steel slag was placed in areas of complaint to find out if road conditions could be improved by using this material.

Test Section 3 is located immediately east of County Road 9 on Concession 4 Road, Lots 4 and 5. It is approximately 1500 m long (Figure B-13). Placing of 150 to 200 mm EAF steel slag GBC B on the existing natural aggregate granular base strengthened this road segment. Top dressing consisted of 25 to 50 mm of EAF steel slag GBC A. Expansion decreased to 0.29 per cent in 1996 (Table 1). Some potholes and washboarding were observed during annual inspections (Figures B-15 and B-16). Dust control and routine maintenance activities were carried out in the same way as on natural aggregate roads. This test section remained unpaved. No further complaints were received from local drivers during the spring thaw, and the material seems to have given satisfactory performance.

Test Section 4 is a continuation of Test Section 3 on Concession 4 Road, Lots 1, 2, and 3. It is approximately 2000 m long (Figure B-14). The purpose of this test section was to document the rate of steel slag expansion decline in a thin layer. A 25 to 50 mm layer of EAF steel slag GBC A was placed on top of the existing 100 to 150 mm natural aggregate GBC B as top dressing. Test results from 1996 indicate that expansion decreased to 0.13 per cent (Table 1). Ten years later, the slag is hard to find as it gradually got mixed in with the majority of natural aggregate in the road and in the shoulder as a result of periodic grading. This test section also remained unpaved. As in Test Section 3, the slag seems to have given satisfactory performance when diluted with natural aggregate on an unpaved road.

Test Section 5 is located on Common Boundary Road north of the intersection of this road with Lake George Road. This test section is approximately 1700 m long. It was constructed of 300 to 450 mm of EAF steel slag GBC B overlain by 25 to 50 mm natural aggregate GBC A as top dressing. The purpose here was to collect expansion data on a thick steel slag layer without the cocooning effect of a cover layer of EAF steel slag GBC A such as in Test Section 2. Expansion in this test section decreased to 0.19 per cent by 1996 (Table 1). This test section was surface treated in 1999 with Class 2 aggregate. Minor randomly distributed cracking became visible in 2001 (Figure B-17), and was observed to increase in frequency in 2002. The cracks had no serious detrimental effect on pavement performance. A section of Common Boundary Road located south of Lake George Road, built with natural aggregate and surface treated in 1999, was also inspected for comparison purposes with the road superintendent present. No cracks were found.

BEDARD STREET

Bedard Street is located in Bedard Estate Subdivision, south of Sandy Hill Road and immediately west of Highway 34, south of the boundary of the Town of Hawkesbury (Figure 2). Bedard Street was also built with EAF steel slag GBC A and B in two stages. The first 350-metre section of the street was built in 1992 and paved with HL3 in 1997. The next 400 metres of the street were built in 1995 with GBC B. Fresh EAF steel slag GBC A was placed just before paving in 1999. The structure of this street is the same as Ravary Street. The existence of this EAF steel slag road came to the attention of the authors in 2001 when the road superintendent expressed concern about some atypical cracks occurring in the pavement at the end of this street. He described the cracks as

"spider cracks". These 100 to 200 mm long cracks appear to originate from a point and tend to advance in three different directions. The pavement is slightly elevated at the junction of the cracks. Some random, 100 to 300 mm, longitudinal cracks were also observed. In 2002, the size and frequency of these cracks were observed to slightly increase. Municipal concern exists about premature pavement deterioration due to the expansion of the EAF steel slag and the need to repave this street sooner than planned. While monitoring and sampling of the EAF steel slag in this road was not part of this study, it is mentioned here to document the possible damaging effects of fresh EAF steel slag when sufficient time is not given to allow the expansion to dissipate to a tolerable level (Figure B-18). A detailed forensic excavation of the cracked areas of this pavement would be required to confirm if expanding EAF steel slag is the prime cause of the observed atypical pavement distress.

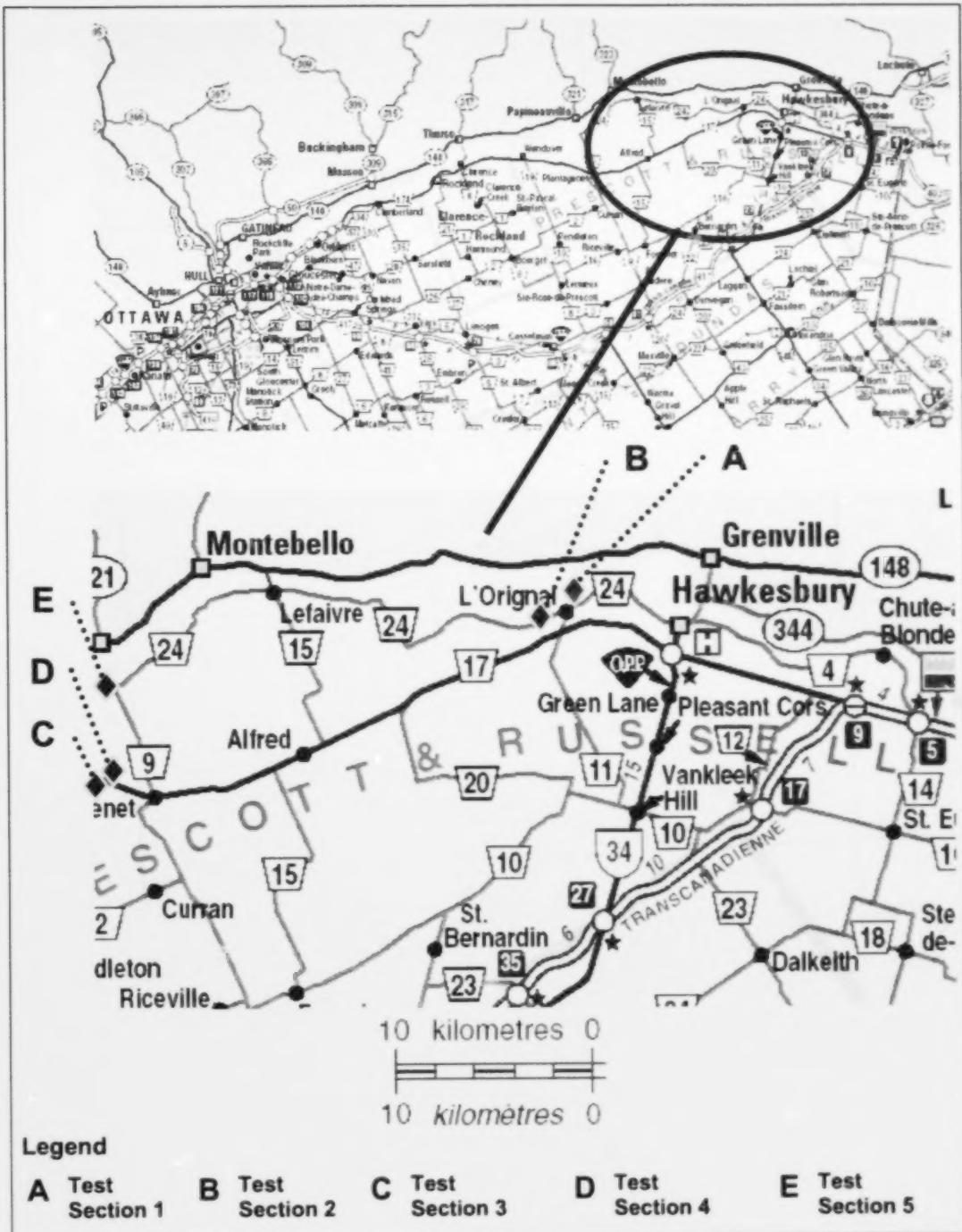


Figure 1 - Test Section Location Map



Test Results and Discussion

The ASTM D 4792 test method was chosen to perform all expansion testing of the fresh EAF steel slag samples collected from the five test sections used in this study. This was the best known and available test method in Ontario and the United States at the start of this experiment. The ASTM D 4792 test method has also been used to evaluate the expansion potential of cured EAF steel slag as pavement material in Brazil [Rhode *et al*, 2003]. This study reported that the steel slag must be stockpiled in the open air for at least four months before it can be used in pavement construction. The authors also mentioned that their conclusion was highly dependent on climatic characteristics. The findings of the Brazilian study pertain to a subtropical humid climate, which is starkly different from the temperate climate of eastern Ontario. Members of the European Union adopted European Standard EN 13043 [CEN, 2002]. This standard also recognizes the use of steel slag aggregates and sets maximum expansion values based on type of steel slag and MgO content. Ultimately, the choice of a preferred test method lies with the purchaser of the material, based on the availability and reliability of the selected test method.

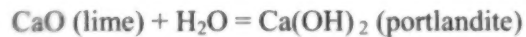
It took three years for an unpaved 150 mm layer of EAF steel slag GBC A in Test Section 1 in the Riviera Estate Subdivision to reach the specification limit for expansion of 0.5 per cent at seven days in the ASTM D 4792 test. This is much longer than the original expectation of the slag supplier of less than 0.5 per cent expansion in less than six months due to in-place curing (Figure 3).

The thicker the layer of the slag in granular base or sub-base, the longer it retains its expansive characteristics. This was clearly demonstrated by Test Section 2 in the Ravary Estate Subdivision. The composite layers of EAF steel slag GBC A and B yielded expansion test results that were more variable than anticipated. The test results did decrease below one per cent overall in 2001. However, from 1994 to 2001 the expansion was unpredictably variable and ranged from a low of 0.33 to a high of 1.90. In Test Sections 3 and 4, layers of less than 250 mm of EAF steel slag appear to indicate a predictable and more gradual decrease of expansion with time. In Test Section 5, a very thin layer of natural aggregate top dressing did not seem to have any impact on the rate of decrease of expansion.

The rate of decrease of expansion is higher for EAF steel slag granular base exposed to the elements than for EAF steel slag granular sub-base covered by EAF steel slag granular base, likely due to the protective effect of the overlying steel slag base layer (Figure 3).

Drainage ditch water associated with large quantities of steel slag can have an elevated pH. Due to their chemical basicity, steel slags have been reported to have pH values in the 10 to 12 range [Emery, 1982]. Small quantities of white-coloured steel slag ditch water precipitate were observed in the ditches at Test Sections 1 and 2 (Figures B-8, B-

11, and B-12). This material was sampled in 2000 and was identified by x-ray diffraction testing as calcite. It has been found that aging of slags by exposure to the weather does not necessarily decrease the free lime content enough to prevent the formation of tufa [Gupta *et al*, 1994]. Basically, as long as the calcium and magnesium oxides are present and moisture is available, the hydration process will continue. While calcite is not a hazardous chemical, its potential to plug drainage in the pavement structure is undesirable. Leachate from thick applications of steel slag may be an aesthetic and environmental concern requiring engineered remedial measures/treatments, or dilution of drainage ditch water. The basic chemical reactions that are believed to be causing expansion of steel slag aggregate and formation of calcite (CaCO_3) are shown below:



All physical laboratory testing was completed by the MTO Downsview testing laboratory (Figures B-19 and B-20). Free lime testing after 1998 was done by Lakefield Research. A summary of all test results is presented in Tables A-1, A-2, and A-3 in Appendix A. These tables indicate that EAF steel slag is a material with variable free lime content. Expansion test results are also variable. There seems to be a proportional relationship between petrographically observed lime and chemically detected free lime (Figure 4).

The Ravary Estate Subdivision material was used in a multi-laboratory correlation study of the ASTM D 4792 test method conducted by MTO in 1995 (Appendix C). This study was limited by having only five qualified laboratories and found a wide degree of variability in the reported expansion test results when coefficient of variation was plotted against expansion. For example, for a mean expansion of less than 0.5 per cent, the average multi-laboratory coefficient of variation when testing one specimen was found to be 25 per cent using four-year-old slag. The average expansion test result reported by the participating laboratories from Canada and the USA was 0.35 per cent at seven days. The MTO expansion test result on the same material before shipment to the participants was 0.33 per cent. To demonstrate test result variability, it is worth noting that the annual sample taken at a different random location in the same test section and also tested by MTO gave an expansion of 0.88 per cent. The probable cause of the difference in test results is variation in steel slag composition and free lime content within the pavement.

Micro-Deval Abrasion (MDA) loss testing was conducted on sixteen EAF steel slag samples taken from Test Section 2. Four GBC A and three GBC B samples were tested for coarse aggregate MDA loss. The average was found to be 12.7 per cent for GBC A and 10.0 per cent for GBC B. These test results are well within the maximum loss specification limit of 25 per cent for GBC A and 30 per cent for GBC B. Five GBC A and four GBC B samples were tested for fine aggregate MDA loss. The average was found to be 26.8 per cent for GBC A and 23.7 per cent for GBC B. These test results are within the maximum loss specification limit of 30 per cent for GBC A and 35 per cent for GBC B. In the case of fine aggregate EAF steel slag samples, higher lime content, as identified by petrographic examination, tends to result in higher MDA losses (Table A-2).

This is to be expected because lime particles are relatively soft compared to other slag components. Permeability test results of EAF steel slag from Test Section 2 indicate that permeability is variable and can decrease over time, possibly due to variation in steel slag composition, free lime content, and extent of carbonation (Table A-2).

**Table 1 - Summary of EAF Steel Slag Expansion Test Results
(ASTM D 4792) from Test Sections 1 to 5**

Test Section	1	2	3	4	5
Location	Township of Champlain Chemin De La Bergerie Road	Township of Champlain Ravary Street	Township of Alfred and Plantagenet Con. 4, Lots 4 and 5	Township of Alfred and Plantagenet Con. 4, Lots 1, 2, and 3	Township of Alfred and Plantagenet Common Boundary Road
Composition	150-250 mm GBC A 300-450 mm Nat GBC B	200-250 mm GBC A 300-450 mm GBC B	25-50 mm GBC A 150-200 mm GBC B	25-50 mm GBC A 100-150 mm Nat GBC B	25-50 mm Nat GBC A 300-450 mm GBC B
Length	1200 m	1500 m	1500 m	2000 m	1700 m
Status	Built in 1991 Paved in 1997	Built in 1992 Paved in 1999	Built in 1992 Not paved	Built in 1992 Not paved	Built in 1992 Surface treated in 1999
Material Tested	GBC A	GBC A GBC B	GBC A & B	GBC A	GBC B
1991	2.79	- -	-	-	-
1992	1.72	2.79 2.84	0.68	1.07	2.67
1993	0.97	0.85 1.79	1.05	0.94	0.31
1994	0.43	0.76 1.58	0.84	0.19	0.73
1995	0.59	0.88, 0.33 1.87	0.74	0.22	0.40
1996	-	1.11 0.42	0.29	0.13	0.19
1997	0.10	0.57, 0.69 1.90, 0.71	-	-	-
1998	-	- -	-	-	-
1999	-	1.17 0.57	-	-	-
2000	-	- -	-	-	-
2001	-	0.87 0.72	-	-	-

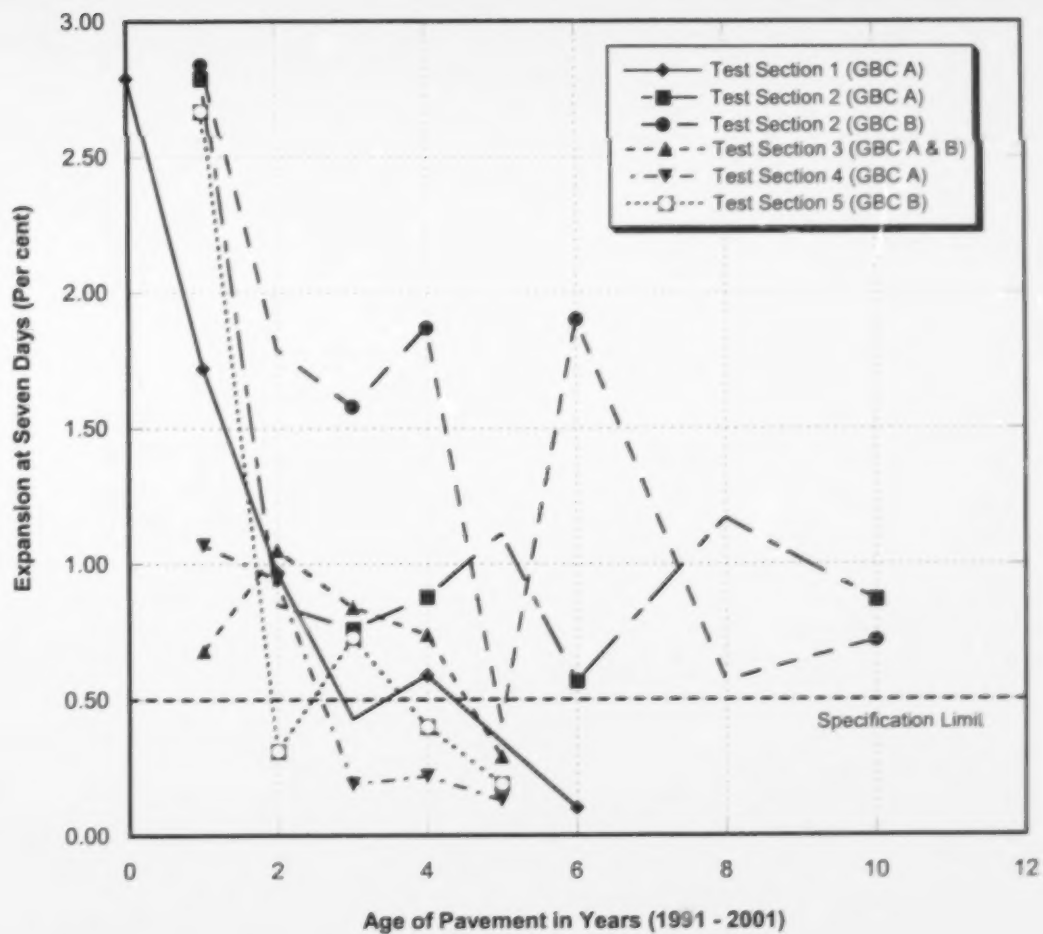


Figure 3 – EAF Steel Slag Expansion Versus Age of Pavement

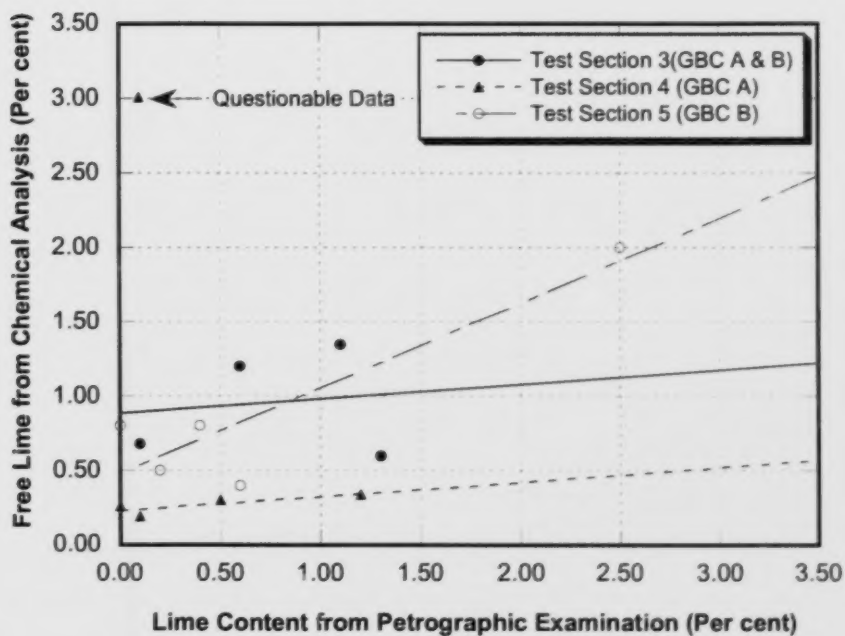
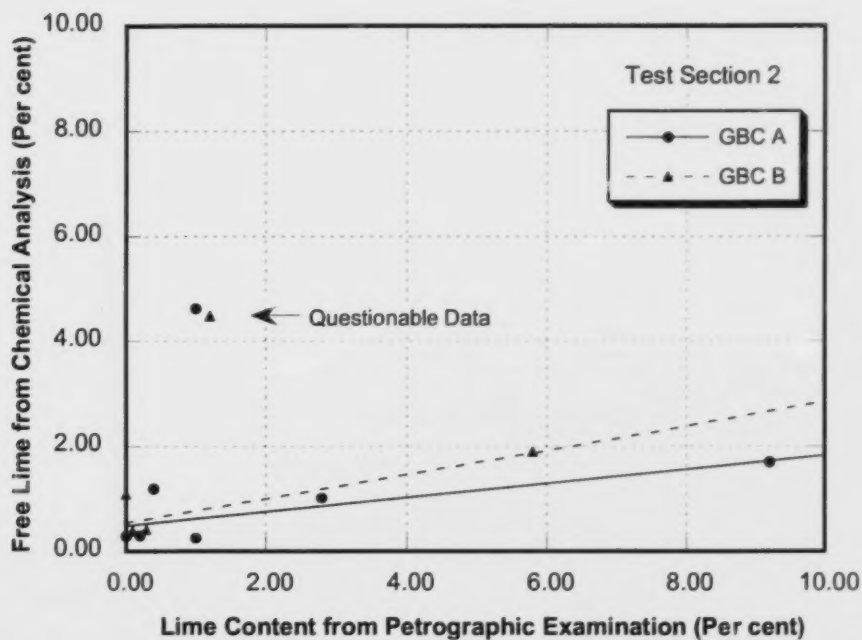


Figure 4 – Free Lime Versus Petrographically Observed Lime

Literature Review

To be considered suitable for use in highways, a waste material must exhibit the proper engineering characteristics, consistently satisfy specification requirements, provide an acceptable level of performance, and be economically competitive with other available construction materials without harming the environment [Collins and Ciesielski, 1994]. The use of steel slag aggregates could result in two major benefits. It would supplement the supply of natural aggregates, thereby extending the life of natural aggregate sources. The rate of consumption of landfill space by waste slag could also be reduced [Woodside *et al*, 1996]. In Ontario, the opportunity to replace natural aggregate materials with recycled aggregate materials in construction, using 1990 data and optimistic use projections, has been estimated to be three to five per cent of total aggregate production [Ontario, 1992]. The ministry has used material from old pavements in granulars since the early 1970s [Senior *et al*, 1994]. Steel slag aggregates would be a small fraction of this amount, with potential local opportunities within economic hauling distance around Ontario steel mills. There is increased public awareness and recognition for the need to recycle. However, basic market economics determines the feasibility and implementation success of such initiatives.

UTILIZATION OF BOF AND EAF STEEL SLAGS IN ROAD CONSTRUCTION

Large heaps of slag piles can be found near iron and steel works in both the industrialized and developing countries of the world. Technical, economic, and ecological criteria are the driving force of desire to find uses for the old and newly generated steel slags. In addition to granular base and sub-base, there are other viable uses for steel slag such as use in hot mix asphalt, granular fill, unpaved shoulders, private roads, bike trails, acid mine drainage treatment, and agriculture. It is noted in the literature that, in the case of steel slag, only weathered steel slag should be used, as fresh steel slag possesses variable amounts of free lime which, on hydration, may lead to volume instability [Boyle and Khati, 1998; Mathur *et al*, 1999]. The alternate to aging or weathering of steel slags is good slag practices in the steel mill and the steel slag-processing plant. Techniques such as oxygen injection of the slag, steam treatment of slag, and careful tracking and sorting of different batches of slag are a few examples of quality control measures to control volumetric instability of steel slag aggregate. The early trials of iron and steel-making slags in road construction were in pavements within the premises of steel works [Nomura and Enokido, 1981]. Research work using various combinations of steel slags, blast furnace slag, granulated slag, fly ash, and lime as subgrade stabilization agents have been documented in the literature [Haga *et al*, 1981; Heaton, 1989; Mathur *et al*, 1999]. Mathur *et al* reported that a slag mixture made up of 50 per cent blast furnace slag, 20 per cent steel slag, 20 per cent granulated slag, 6 per cent fly ash, and 4 per cent lime has been shown to possess properties adequate for consideration as a bound sub-base or base layer in road pavement. These kinds of applications are the more sophisticated approaches taken to the utilization of slags in road base and sub-base applications. These applications could also be tried out in the Hamilton and Sault Ste. Marie areas of Ontario.

An exact duplicate of the experiment documented in this report was not found in the literature.

In Germany, the use of slags as an aggregate for civil engineering, for metallurgical use and as fertilizer has a long tradition. Much research has been done in Germany on the development of fields of application of BOF and EAF slags. The diverse use of steel slags has been made possible because the steel works improve the quality of slags by careful selection of raw materials and a suitable process route. Furthermore, subsequent procedures like a treatment of the liquid slag, an appropriate heat treatment, and a suitable processing have been developed to ensure that the quality of steel slags is adequate for the end use. In Germany in 1998, about 97 per cent of steel slags were used as aggregates for road construction as surface course, base, and sub-base in high-volume roads [Moitz and Geiseler, 2001]. In Ontario, some steel makers have made efforts to improve the quality of their steel slag for hot mix aggregate applications since 1991. One major steel mill examined its steel-making practices and slag processor, and concluded that the production of acceptable quality steel slag aggregate requires total quality management of all steps of production [Farrand and Emery, 1995].

ENVIRONMENTAL AND HEALTH CONSIDERATIONS OF STEEL SLAG USE

Prospective purchasers of slag aggregates often raise questions regarding the use of steel slag in various applications because of its elevated metal content and the associated potential for impacts on the environment and human health. The most comprehensive American study to date was published in 2000 [Proctor *et al.*, 2000]. This study addressed physical and chemical characteristics of blast furnace, BOF, and EAF steel industry slags based on samples collected in 1995 and 1996 from 58 steel mills in USA and Canada. This study found that, although concentrations of metals in slag are elevated relative to concentrations in soil, the metals are tightly bound to the slag silicate minerals and not readily leached. The Steel Slag Coalition of the USA has published risk assessment conclusions derived from this study [Wittenborn and Green, 1998]. Its conclusions are quoted below:

"Steel slag poses no significant health risks for potentially exposed residential populations, farmers, or maintenance, industrial and construction workers.

Metals in steelmaking slag will not leach readily into groundwater or surface water and, therefore, will not affect drinking water quality.

Steel making slag will not impact animals and other terrestrial life in or near areas of application. Metals in steelmaking slag do not bioaccumulate in the food web and are not expected to bioconcentrate in plant tissue.

Steelmaking slag may be applied safely in aquatic environments such as rivers, lakes and streams without impacting water quality or aquatic life. Such aquatic environments normally provide sufficient dilution (at least 1,000-fold) to protect against possibly elevated pH levels and, in the case of EAF slag, potential concentrations of aluminium and barium. Care should be taken when applying slag in smaller aquatic bodies where low water flow conditions exist, such as wetlands or shallow ditches."

In 1998, the MTO Steel Slag Subcommittee advised the Ontario steel-making industry that it must negotiate a protocol on the use of steel slag with MOE prior to the use of slag by MTO. These negotiations will have to include the issue of high pH, and the protocol should include any and all restrictions and/or conditions associated with the use of steel slag. Use of steel slag in compliance with a protocol endorsed by MOE will ensure that the requirements of the Environmental Protection Act (EPA) and the Ontario Water Resources Act (OWRA) have been addressed [Ontario, 1998].

Conclusions

This long-term experiment provided engineering data that indicate that fresh EAF steel slag, when used in the same manner as natural aggregate, can be used successfully as granular base and sub-base in low-volume roads. Special care must be taken in choosing the most appropriate application to mitigate problems arising from inherent variable chemical composition and the unknown amount of expansion potential remaining in the material. These material characteristics are tied to the batch method of steel-making processes used in Ontario steel mills. Technical literature on this subject indicates that technology exists to produce a more consistent and less expansive steel slag aggregate product [Farrand and Emery, 1995]. This will require increased quality control and quality assurance measures.

MTO use of this material would not be practical, due to the fact that high-volume provincial highways need to be paved as quickly as possible, unless suppliers establish stockpiles that have been allowed to achieve an acceptable level of expansion. Considerations for granular base and sub-base low-volume road applications, subject to local environmental use approval, are given below.

Steel Slag Granular Base Over Natural Aggregate Sub-Base or Maintenance Application

- Fresh steel slag should not be used as backfill for structures, culverts, sewers, or other locations where the expansive behaviour of the material may cause harm to structures.
- Fresh steel slag must be aged or treated to reduce potential expansion to a satisfactory level in the road before asphalt paving or surface treatment.
- Before any paving or application of surface treatment, the owner must ensure that the steel slag has expansion values below 0.50 per cent at seven days when tested in accordance with ASTM Test Method D 4792.

Steel Slag Granular Base over Steel Slag Granular Sub-Base Application

- Same as above.

The above considerations and choices of ASTM test method and specification reflect the preference of the authors solely for the purpose of the experiment documented in this report. They do not represent any MTO policy, standard, or specification regarding steel slag aggregate use in provincial highway construction.

Recommendations

1. EAF steel slag is not recommended for ministry use. Slags that are known to be even more expansive are also not recommended for ministry work. Variability in steel slag composition and unpredictable expansion behaviour are the prime concerns. Appropriate quality control measures and treatment by the Ontario steel-making industry would be required to improve engineering and environmental quality of this material before ministry use could be considered. Time is of the essence on ministry contracts, excluding the use of in-place curing of fresh steel slag aggregate.
2. Test sections demonstrated the successful use of fresh EAF steel slag in unpaved low-volume road applications in thin maintenance lifts in granular base, sub-base, or shouldering over natural select subgrade material. In these applications, the EAF steel slag would ultimately be blended in with the natural aggregate materials. Paving or surface treatment must not occur immediately, allowing sufficient time for the rate of expansion of the fresh steel slag to decrease to a tolerable level.
3. Sufficient test data have been collected to document long-term EAF steel slag expansion behaviour. Since key test sections have been paved over, sample collection should stop. Field observations indicate that steel slag has performed well since paving. Field observations of the pavements should continue, in order to document long-term performance of the test section roads and the overlying hot mix asphalt.

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Appendix A: Laboratory Test Results

Table A-1 – Summary of EAF Steel Slag Test Results from Test Section 1: Chemin De La Bergerie Road

Year	Material	MTO LS-616			MTO LS-706		MTO LS-701	MTO LS-709	MTO LS-622	ASTM D 4792		
		Petrographic Examination (Total % by Mass)			Proctor Density		MC (%)	Permeability K (cm/s)	Free Lime CaO (%)	Expansion (%) Days		
		Slag	Non Slag	Lime	Wood	MDD	OMC (%)			7	14	Max. (Days)
1991	GBC A	98.6	1.4	0.0	0.0	2.551	5.9	-	0.17	2.79	-	-
1992	-	-	-	-	-	-	-	-	-	1.72	-	-
1993	GBC A	-	-	-	-	-	-	8.0	0.62	0.97	1.73	-
1994	GBC A	99.5	0.5	0.0	0.0	2.555	9.9	8.0	0.09	0.43	1.00	-
1995	GBC A	96.8	3.2	0.0	0.0	2.443	10.1	5.5	0.31	0.59	1.24	-
1996	-	-	-	-	-	-	-	-	-	-	-	-
1997	GBC A	99.8	0.2	0.0	0.0	2.474	7.1	-	0.18	0.10	-	-

Abbreviations and Titles of Test Methods

GBC A = Granular Base Course A GBC B = Granular Sub-Base Course B MC = Moisture Content
 MDA = Micro-Deval Abrasion MDD = Maximum Dry Density OMC = Optimum Moisture Content
 ASTM D 4792 Standard Test Method for Potential Expansion of Aggregates from Hydration Reactions
 Relative Density and Absorption of Coarse Aggregate
 Petrographic Analysis of Fine Aggregate
 MTO LS-604 The Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus
 MTO LS-616 The Resistance of Fine Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus
 MTO LS-618 Free Lime Content of Steel Slag Aggregates
 MTO LS-619 Determination of Moisture Content of Soils
 MTO LS-622 Moisture Density Relationship of Soils Using 2.5 kg Rammer and 305 mm Drop
 MTO LS-701 Determination of Permeability of Granular Soils
 MTO LS-706
 MTO LS-709

Table A-2 – Summary of EAF Steel Slag Test Results from Test Section 2: Ravary Street

Year	Material	MTO LS-616				MTO LS-618/619		MTO LS-604 Bulk Relative Density	MTO LS-604 Abs'n (%)	MTO LS-709 Permeability K (cm/s)	MTO LS-622 Free Lime CaO (%)	ASTM D 4792		
		Petrographic Examination (Total % by Mass)				MDA Loss (%)						Expansion (%) Days		
		Slag	Non Slag	Lime	Wood	CA	FA					7	14	Max. (Days)
1992	GBC A (fresh)	99.4	0.2	0.4	0.0	-	-	-	-	1.9×10^{-3}	1.20	2.79	4.36	7.61 (39)
	GBC B (fresh)	98.5	1.5	0.0	0.0	-	-	-	-	2.0×10^{-3}	1.09	2.84	4.14	8.32 (36)
1993	GBC A (1YR)	95.1	2.1	2.8	0.0	-	-	-	-	3.3×10^{-3}	1.02	0.85	1.65	-
	GBC B (1YR)	-	-	-	-	-	-	-	-	2.4×10^{-3}	0.59	1.79	2.81	-
1994	GBC A (2YR)	99.1	0.9	0.0	0.0	-	-	-	-	4.3×10^{-5}	0.29	0.76	1.41	-
	GBC B (2YR)	99.1	0.9	0.0	0.0	-	-	-	-	3.8×10^{-4}	0.36	1.58	2.79	-
1995	GBC A (3YR)	96.5	3.2	0.2	0.0	-	-	-	-	2.3×10^{-4}	0.30	0.88	1.76	-
	GBC B (3YR)	97.8	2.1	0.1	0.0	-	-	-	-	4.0×10^{-5}	0.40	1.87	3.22	-
1996	GBC A (RR)	94.7	5.3	0.0	0.0	11.2	18.6	3.107	3.395	3.9×10^{-4}	0.20	0.33	0.59	0.87 (21)
	GBC A (4YR)	87.3	3.5	9.2	0.0	12.3	30.6	3.164	3.221	3.5×10^{-4}	1.70	1.11	2.49	-
1997	GBC B (4YR)	90.7	3.5	5.8	0.0	11.5	29.0	3.340	2.307	6.2×10^{-2}	1.90	0.42	0.79	-
	GBC A (5YR)	-	-	-	-	-	-	-	-	-	-	0.57	-	-
1997	GBC B (5YR)	-	-	-	-	-	-	-	-	-	-	1.90	-	-
	GBC A (5YR)	84.4	14.6	1.0	0.0	15.5	25.0	3.138	3.806	impermeable	0.26	0.69	-	-
1999	GBC B (5YR)	98.6	1.2	0.3	0.0	9.3	22.1	3.330	2.815	impermeable	0.42	0.71	-	-
	GBC A (7YR)	91.4	7.0	1.6	0.0	11.9	31.0	3.044	4.020	-	-	1.17	2.10	3.70 (24)
2001	GBC B (7YR)	98.2	1.7	0.1	0.0	9.2	21.1	3.362	2.701	-	-	0.57	1.18	2.03 (24)
	GBC A (9YR)	94.8	4.2	1.0	0.0	-	28.8	3.077	4.290	1.5×10^{-4}	4.62	0.87	2.13	-
2001	GBC B (9YR)	97.9	0.9	1.2	0.0	-	22.7	3.284	2.844	2.8×10^{-2}	4.48	0.72	0.89	-

Abbreviations and Titles of Test Methods

GBC A = Granular Base Course A
 GBC B = Granular Sub-Base Course B
 ASTM D 4792 = Micro-Deval Abrasion
 Standard Test Method for Potential Expansion of Aggregates from Hydration Reactions
 MTO LS-604 = Relative Density and Absorption of Coarse Aggregate
 MTO LS-616 = Petrographic Analysis of Fine Aggregate
 MTO LS-618 = The Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus
 MTO LS-619 = The Resistance of Fine Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus
 MTO LS-622 = Free Lime Content of Steel Slag Aggregates
 MTO LS-701 = Determination of Moisture Content of Soils
 MTO LS-706 = Moisture Density Relationship of Soils Using 2.5 kg Rammer and 305 mm Drop
 MTO LS-709 = Determination of Permeability of Granular Soils

CA = Coarse Aggregate
 FA = Fine Aggregate
 MC = Moisture Content
 OMC = Optimum Moisture Content

RR = Round Robin

Table A-3 – Summary of EAF Steel Slag Test Results from Test Sections 3, 4, and 5:
Township of Alfred and Plantagenet

Year	Material (Test Section)	MTO LS-616				MTO LS-706		MTO LS-701	MTO LS-709	MTO LS-622	ASTM D 4792		
		Petrographic Examination (Total % by Mass)				Proctor Density					Expansion (%)		
		Slag	Non Slag	Lime	Wood	MDD	OMC (%)				7	14	Max. (Days)
1992	GBC B & A (3)	99.0	0.9	0.1	0.0	-	-	5.5	4.9×10^{-2}	3.01	0.68	1.53	3.50 (35)
	GBC A (4)	85.8	14.2	0.0	0.0	-	-	3.5	5.7×10^{-4}	0.26	1.07	1.59	2.23 (35)
	GBC B (5)	85.0	12.5	2.5	0.0	-	-	5.5	5.8×10^{-5}	2.00	2.67	4.25	6.65 (35)
1993	GBC B & A (3)	95.7	3.2	1.1	0.0	2.570	7.6	14.0	2.9×10^{-4}	1.35	1.05	1.66	-
	GBC A (4)	98.1	0.7	1.2	0.0	2.535	8.4	8.0	8.7×10^{-3}	0.34	0.94	1.42	-
	GBC B (5)	97.7	2.3	0.0	0.0	2.581	7.5	6.5	2.3×10^{-4}	0.80	0.31	0.65	-
1994	GBC B & A (3)	85.2	14.7	0.1	0.0	2.523	8.4	5.0	-	0.68	0.84	1.41	2.38 (25)
	GBC A (4)	57.5	42.4	0.1	0.0	2.430	8.8	4.0	2.1×10^{-6}	0.19	0.19	0.27	0.39 (25)
	GBC B (5)	93.3	6.6	0.2	0.0	2.532	8.3	5.0	1.4×10^{-3}	0.50	0.73	1.26	2.10 (25)
1995	GBC B & A (3)	97.8	0.9	1.3	0.0	2.569	8.2	-	1.6×10^{-3}	0.60	0.74	1.72	2.19 (21)
	GBC A (4)	83.6	15.9	0.5	0.0	2.513	8.6	-	3.2×10^{-3}	0.30	0.22	0.41	0.49 (21)
	GBC B (5)	98.5	0.9	0.6	0.0	2.511	7.9	-	1.8×10^{-3}	0.40	0.40	0.88	1.29 (21)
1996	GBC B & A (3)	65.3	34.1	0.6	0.0	2.495	7.1	4.4	1.42×10^{-3}	1.20	0.29	0.50	-
	GBC A (4)	-	-	-	-	2.497	6.4	2.9	2.9×10^{-3}	0.00	0.13	0.15	-
	GBC B (5)	66.5	33.1	0.4	0.0	2.442	7.0	0.0	4.1×10^{-3}	0.80	0.19	0.22	-

Abbreviations and Titles of Test Methods

GBC A = Granular Base Course A
 MDA = Micro-Deval Abrasion
 ASTM D 4792
 MTO LS-604
 MTO LS-616
 MTO LS-618
 MTO LS-619
 MTO LS-622
 MTO LS-701
 MTO LS-706
 MTO LS-709

GBC B = Granular Sub-Base Course B
 MDD = Maximum Dry Density
 Standard Test Method for Potential Expansion of Aggregates from Hydration Reactions
 Relative Density and Absorption of Coarse Aggregate
 Petrographic Analysis of Fine Aggregate
 The Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus
 The Resistance of Fine Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus
 Free Lime Content of Steel Slag Aggregates
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 Moisture Density Relationship of Soils Using 2.5 kg Rammer and 305 mm Drop
 Determination of Permeability of Granular Soils

MC = Moisture Content
 OMC = Optimum Moisture Content

Appendix B: Photographs of Test Sections



Figure B-1 – Unprocessed EAF Steel Slag at IMS Ltd., 1990



Figure B-2 – EAF Steel Slag Aggregate Production at IMS Ltd., 1990



Figure B-3 – Trench Sampling of Test Section 1, Riviera Estate Subdivision, 1993



Figure B-4 – EAF Steel Slag GBC A Road with Proper Ditching, Riviera Estate Subdivision, 1996



Figure B-5 – Extension of Road Network with EAF Steel Slag GBC B, Riviera Estate Subdivision, 1999



Figure B-6 – Riviera Estate Subdivision Road After Four Years of Service, 2001
(Note: High area of pavement damaged by snowplow blade.)



Figure B-7 – Construction of Test Section 2, Ravary Estate Subdivision, 1992



Figure B-8 – Drainage Ditch, Ravary Estate Subdivision, 1996

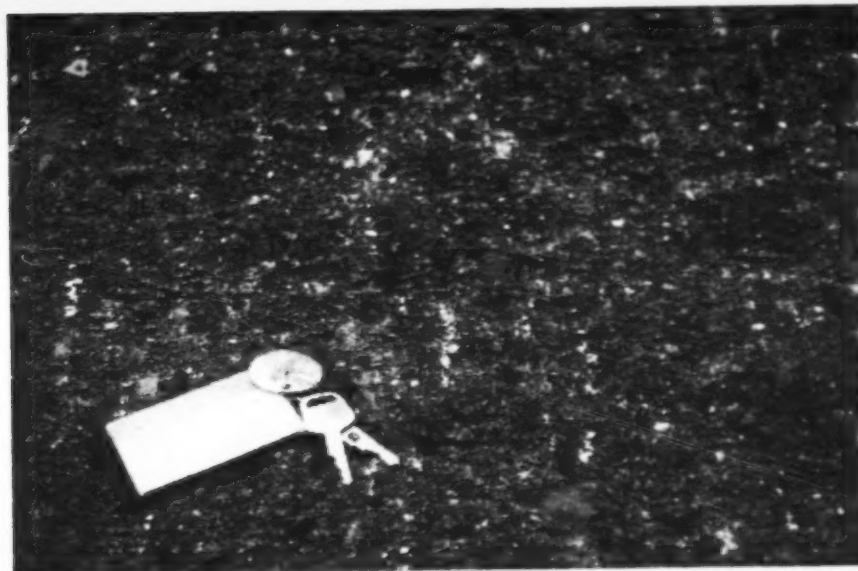


Figure B-9 – Lime in GBC A, Ravary Estate Subdivision, 2001

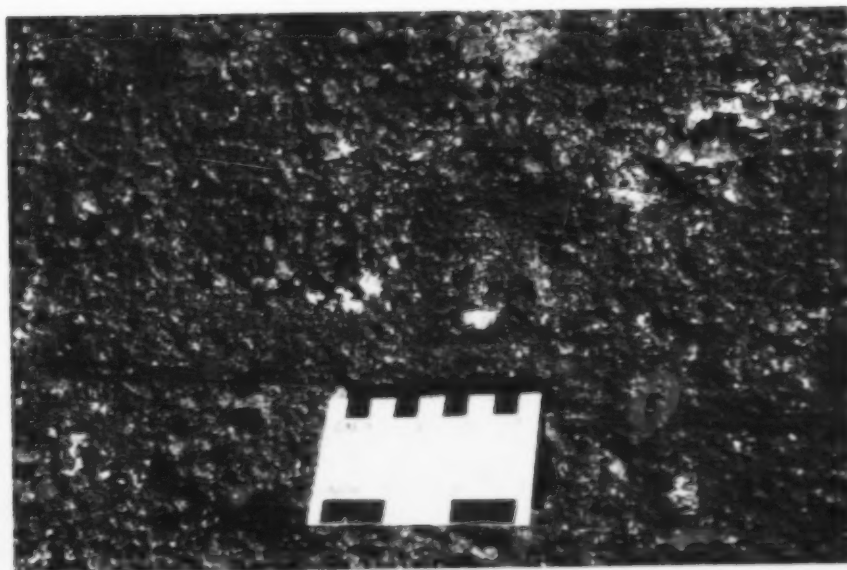


Figure B-10 – Lime in GBC B, Ravary Estate Subdivision, 2000



Figure B-11 – Close-up of Calcite, Ravary Estate Subdivision, 2000



Figure B-12 – Paved Test Section 2, Ravary Estate Subdivision, 2001



Figure B-13 – Test Section 3 Inspection, North Plantagenet Township, 1992
(Note: Dust on vehicles.)



Figure B-14 – Test Section 4 Road Sampling, North Plantagenet Township, 1993



Figure B-15 – Test Section 3 Slight Potholing, North Plantagenet Township, 1996



Figure B-16 – Test Section 3 Potholes, North Plantagenet Township, 2001

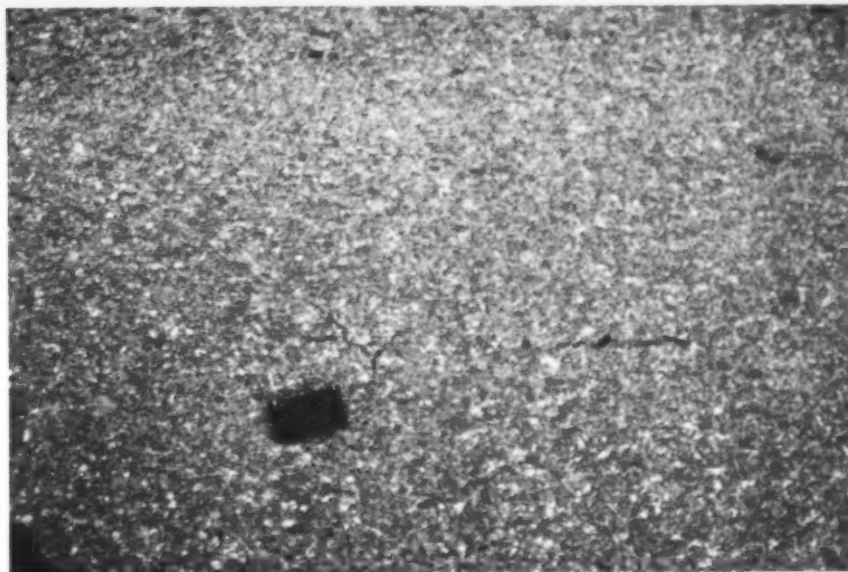


Figure B-17 – Test Section 5 Cracks in Surface Treated Road Underlain by EAF Steel Slag GBC B, North Plantagenet Township, 2001

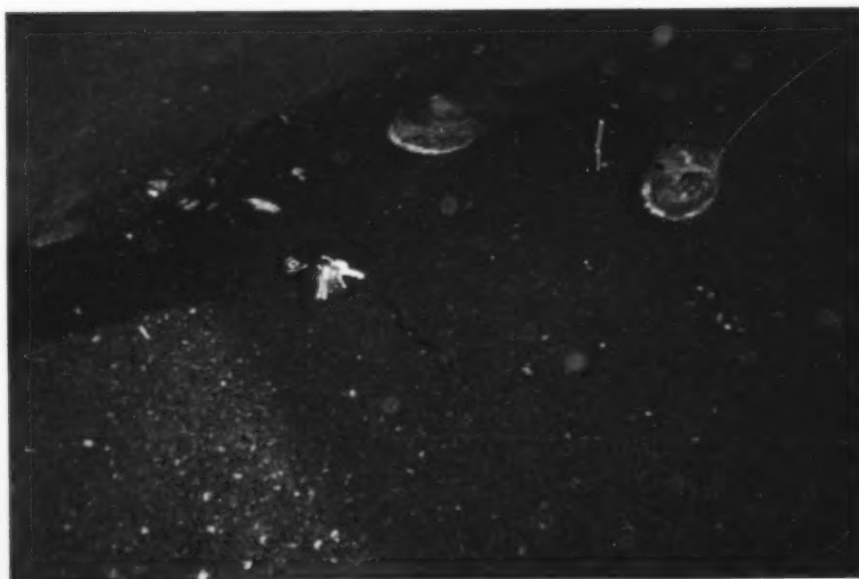


Figure B-18 – Example of Cracks in Residential Driveway Pavement Underlain by EAF Steel Slag GBC A, Former Village of L'Original, 1993



Figure B-19 – Steel Slag Testing Set-up as per ASTM D 4792, MTO Downsview Laboratory, 1993



Figure B-20 – Steel Slag Expansion Testing in Temperature-Controlled Bath and Oven as per ASTM D 4792, MTO Downsview Laboratory, 1993

Appendix C: Multi-Laboratory Study

Draft report for committee use, prepared June 13, 1997, by C. Rogers

Multi-Laboratory Study of the ASTM Test Method for Potential Expansion of Aggregates from Hydration Reactions (ASTM D 4792)

Design of Multi-Laboratory Study

This test is normally used to measure the potential volume expansion of compacted steel slag aggregates. These aggregates typically contain materials (calcium and magnesium oxides) that will hydrate and cause expansion on wetting. The procedure is based on one originally adopted by the Pennsylvania Department of Transportation. A critical difference between the two procedures is that the Pennsylvania test calls for using an oven set at 70°C in which a water bath is placed. The ASTM test calls for the temperature of the water bath to be 70°C. This difference led to difficulties as discussed below. The version of the test studied was ASTM D 4792.

There are very few laboratories in North America that conduct this test. They are situated in the northern mid-western and eastern United States and in Ontario, Canada. The test requires a Proctor density test to determine optimum moisture before making the expansion specimens. As a result, relatively large amounts of material are needed. In order to minimize shipping costs and test complexity, the following design was selected:

Each laboratory would test two samples of steel slag, but only one specimen of each would be tested (the procedure requires 3).

The samples would be from the same location and the same slag.

Material A would not require a Proctor test and would be compacted at a moisture content determined by the co-ordinating laboratory (9.1 per cent).

Material B would have its optimum density determined by the participating laboratory, which would then compact fresh material at that moisture content as required by the test method. This would allow us to see the influence of variations in degree of compaction on multi-laboratory variability. Future multi-laboratory studies would be made considerably easier and cheaper if density variation did not significantly influence expansion variability.

Testing would be conducted for at least 21 days. Measurements would be taken every day, if possible, to maximize the amount of data for numerical analysis.

Steel Slag Testing Material

The material selected for testing was an electric arc steel slag from Hawkesbury, Ontario. The particular material sampled was from an experimental low-volume road where the slag had been used as a granular base course for a period of three years. The slag had been manufactured in 1992 and was sampled in October 1995. This material was selected because it was likely to be a relatively low expansion slag and give an expansion of about 1 per cent at 7 days. As it turned out, it exhibited only about 0.3 per cent expansion. The material was sampled by digging a trench across the road with a backhoe. Approximately 1000 kg were obtained. In the laboratory, the slag was not oven dried. It was mixed, placed in a conical pile, and quartered, and four smaller piles were created. Samples were prepared by scooping equal amounts from each pile. Samples were placed in airtight plastic buckets and shipped to the participating laboratories. Each laboratory received three 18-kg samples, one for sample A and two for sample B.

The slag had a bulk relative density of 3.11. The grading is shown in Table 1. This material had a maximum dry compacted density of about 2330 kg/m³ or 145 lb/ft³ at an optimum moisture content of about 10 per cent.

Table 1. Grading of Representative Sample of Steel Slag

Sieve, mm	% Passing
19.0	99.6
16.0	94.5
13.2	88.0
9.5	74.8
6.7	61.3
4.75	50.7
2.36	35.0
1.18	22.3
0.600	15.0
0.300	10.3
0.150	6.6
0.075	3.7

Laboratories

Ten laboratories volunteered to participate. Results were received from seven laboratories. These seven laboratories had conducted the test before and could be judged to be experienced.

Treatment of Data

Of the seven sets of data received, those from two laboratories were dropped from further analysis. Both of these laboratories had stored the steel slag at a lower temperature than specified in the test procedure ($71 \pm 3^\circ\text{C}$). One laboratory had recorded water temperatures of 62.2 - 67.8°C and 65.0 - 68.3°C , the other a temperature of 46.7 - 57.7°C . Both of these laboratories reported significantly less expansion than the laboratories, which followed the test method. It seems likely that these laboratories had set an oven temperature of 70°C but did not realize that a higher temperature would be needed to maintain the water in the oven at the required temperature.

Because of the shortage of test data, the non-participating laboratories were asked for their samples so they could be retested by others. One sample was obtained and this was tested by Laboratory 2. This was done a year later than the original test by a different testing technician. For the purposes of multi-laboratory study, this could be regarded as another laboratory. The second test by Laboratory 2 is designated in the report as being done by Laboratory 6. There was sufficient material to conduct only an expansion test at the density designated by the co-ordinating laboratory (Material A).

Expansion data is reported in the attached tables. Mean expansion and sample standard deviation are reported for each age at which all laboratories reported expansion. In about 5 per cent of the cases, data were estimated by interpolation between earlier and later ages when missing for specific days. The error is judged to be slight. Laboratory 1 reported an unusual increase in expansion of Material B between days 8 and 9 when expansion nearly doubled from 0.349 per cent to 0.676 per cent. Such an increase is unusual and was not characteristic of other laboratories' experience. Although no reason could be detected it was decided to exclude its data beyond 8 days for that material from analysis. It is possible that it was testing a sample that was somehow different from the others, and the variation experienced was due to the sample rather than test variation.

Figures 1 to 5 show expansion data in graphical form.

Estimate of Precision

Figures 6, 7, and 8 show graphs of sample standard deviation and coefficient of variation against mean expansion at various ages. It can be seen in Figure 6 that, as expansion increases, so does standard deviation. Unfortunately, the data show a fair bit of scatter. This may be due to lack of a proper number of participants rather than an inherent feature of the process. Figures 7 and 8 show expansion against coefficient of variation. In these graphs two different curves are shown. Neither gives a simple way of expressing precision.

ASTM C 802 suggests that, in this situation, precision is probably best expressed for different levels of the property. The average coefficient of variation for expansion less than 0.5 per cent is 24.6 per cent and, for expansion greater than 0.5 per cent, it is 18.0 per cent. These values can be used in the following statement of precision:

For expansion of less than 0.5 per cent, the average multi-laboratory coefficient of variation when testing one specimen has been found to be 25 per cent; therefore, the difference in results reported by different laboratories on samples of the same material should not differ by more than 71 per cent of their average, nineteen times in twenty.

For expansion of more than 0.5 per cent, the average multi-laboratory coefficient of variation when testing one specimen has been found to be 18 per cent; therefore, the difference in results reported by different laboratories on samples of the same material should not differ by more than 51 per cent of their average, nineteen times in twenty.

Recommendations

The data reported here are based on results using a small number of laboratories. As a result, it is unlikely that a true picture of precision has been obtained. Further studies should be conducted when a larger number of qualified laboratories are available.

The precision statement given above can be used in the test procedure with the notation that these data were obtained with between four and six laboratories and thus should be regarded as preliminary.

The variation found with material A and material B was very similar. In the test of material A, each laboratory used a moisture content set by the co-ordinating laboratory. In future studies, in order to reduce costs and complexity, the participants could test samples of steel slag at a predetermined moisture content and omit the determination of maximum density and optimum moisture content required by the test procedure.

The test procedure needs some modification. In 5.3, it implies that tanks or buckets placed in an oven controlled at 70°C will have a water temperature of 70°C. The oven temperature normally has to be set higher than 70°C to obtain the correct water temperature. 5.3 should be changed as follows:

“...in an oven controlled at that temperature” should be replaced with “...in an oven controlled so as to obtain that water temperature”.

The test procedure should also be tightened up to require the monitoring of water temperature on a daily or continuous basis as follows:

9.5 Measure and record the temperature of the water bath on a continuous or daily basis.

11.1.6 A record of the temperature of each water bath.

Acknowledgements

The cheerful involvement and helpful staff of the participating laboratories are gratefully acknowledged. The following laboratories took part in the study: The Levy Co. in Portage, Indiana; the Ontario Ministry of Transportation in Toronto, Ontario; John Emery Geotechnical Engineering Ltd. in Toronto, Ontario; International Mill Services in Coatesville, Pennsylvania; Lafarge Construction Materials in Canfield, Ohio; the National Aggregates Association in Silver Spring, Maryland; and the Pennsylvania Department of Transportation in Harrisburg, Pennsylvania.

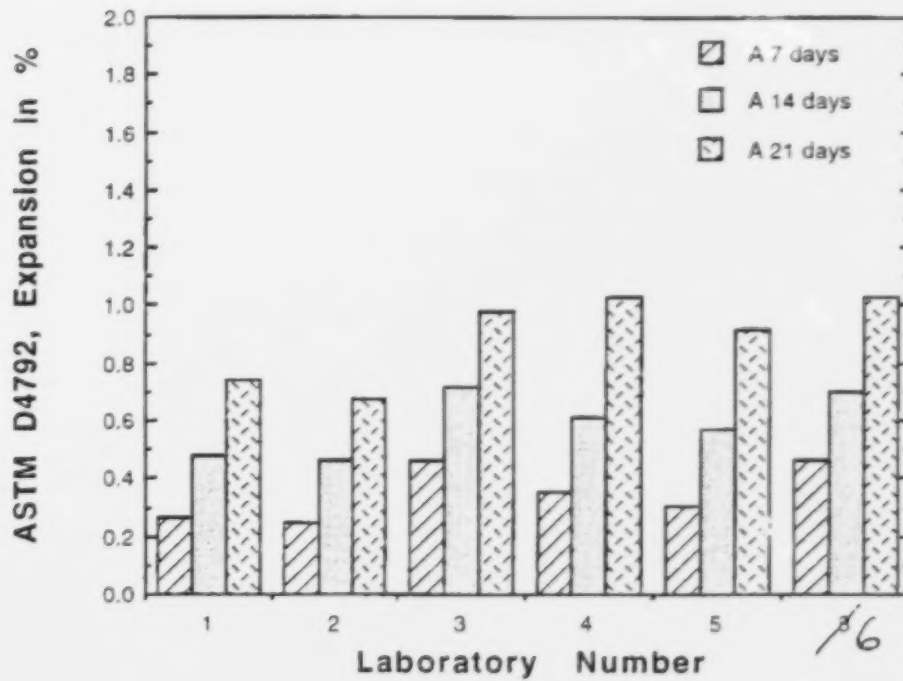


Figure 1

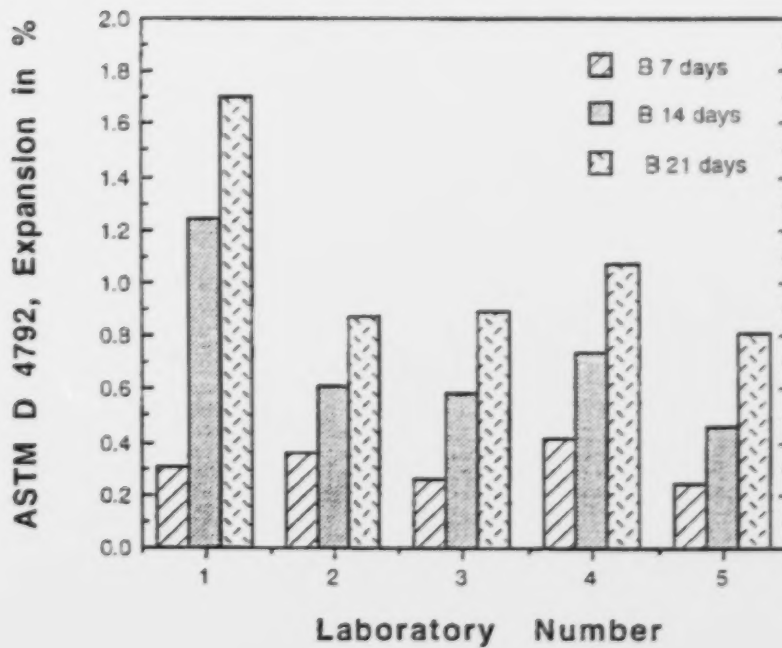


Figure 2

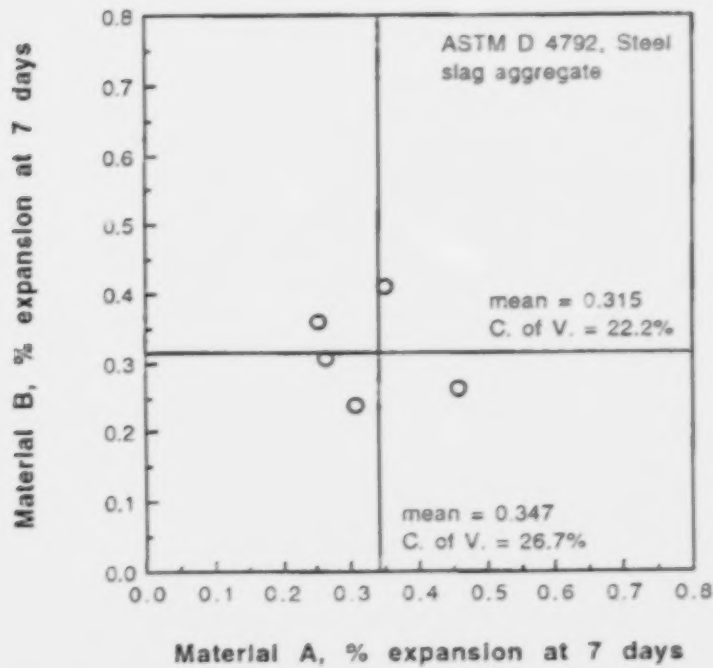


Figure 3

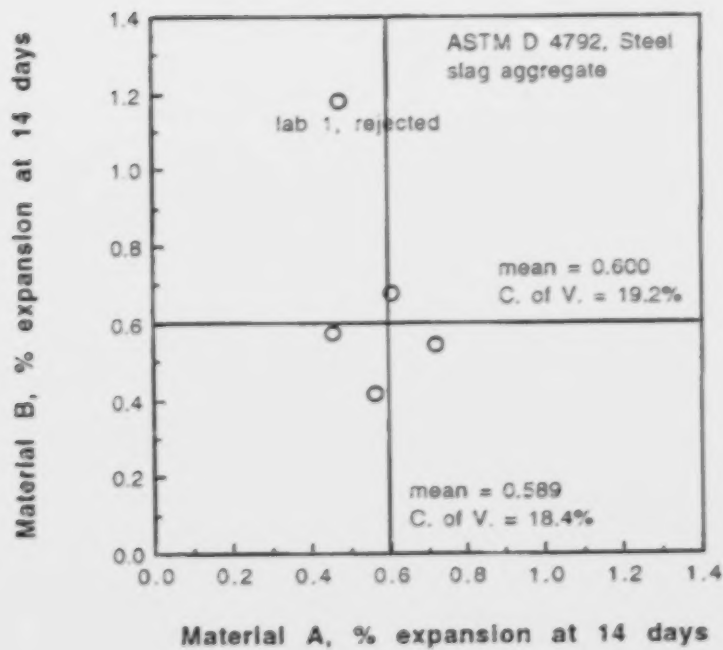


Figure 4

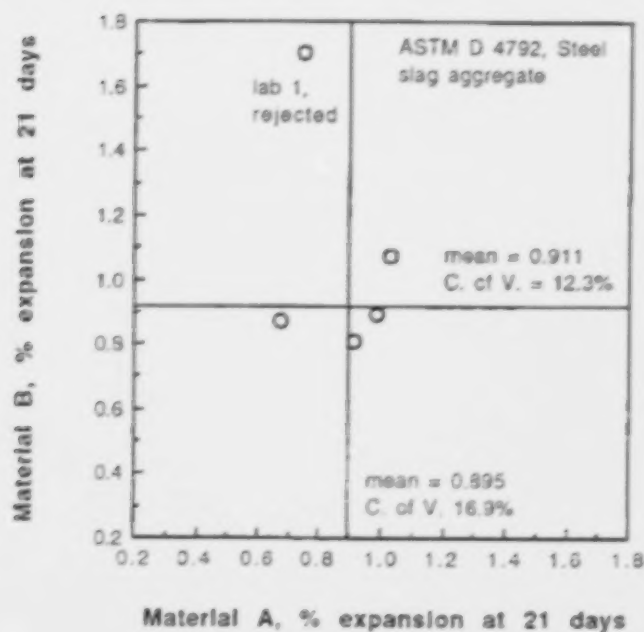


Figure 5

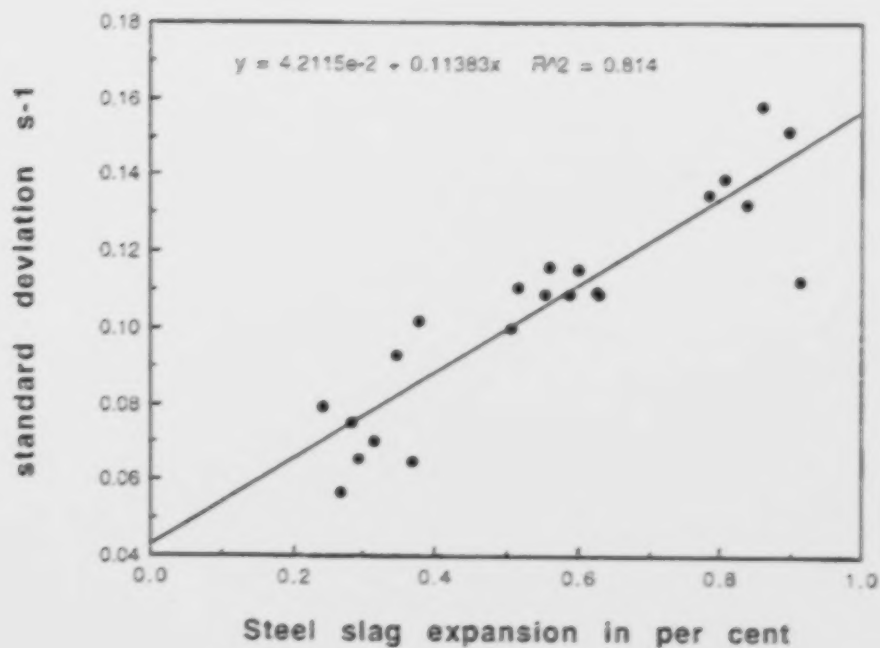


Figure 6

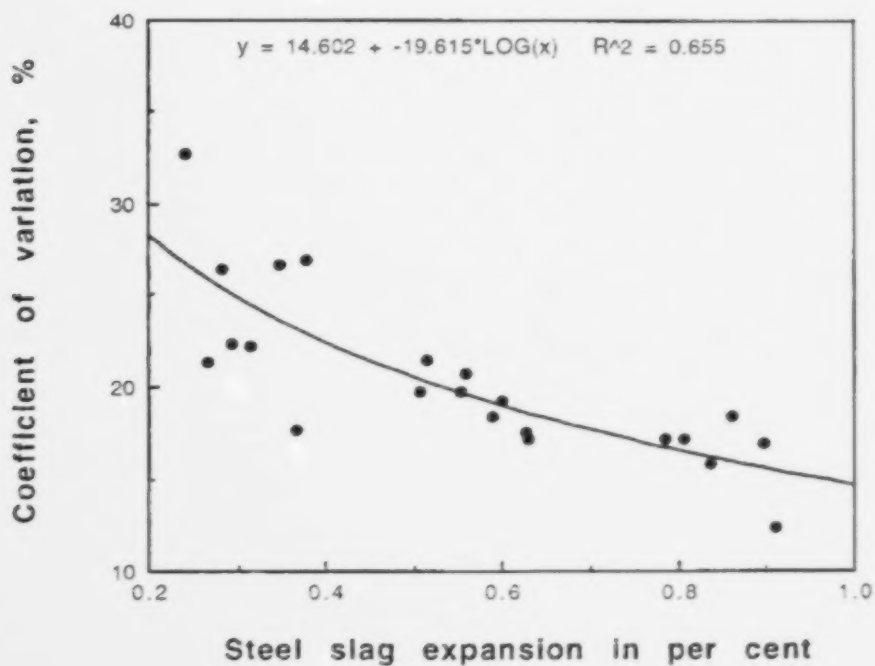


Figure 7

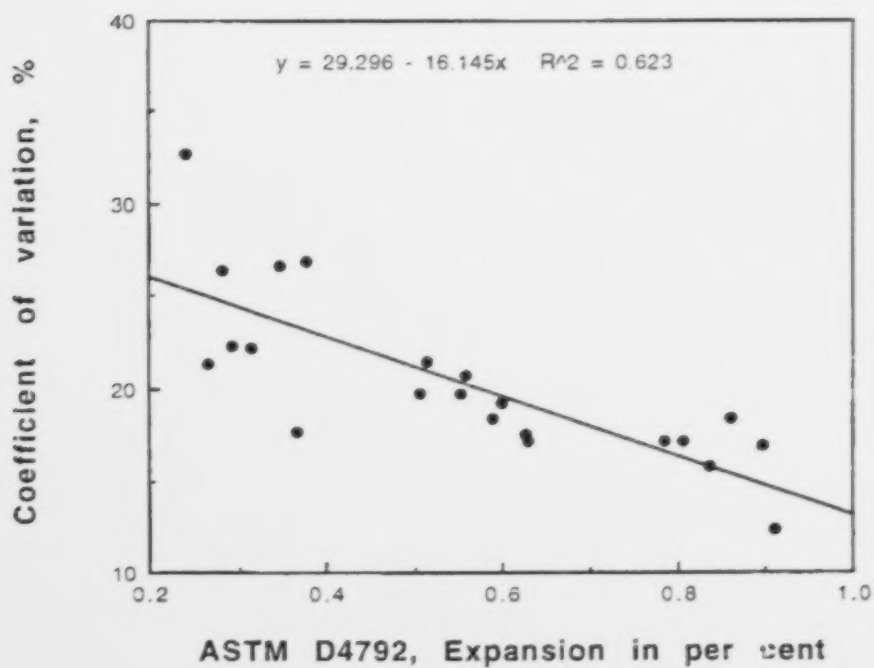


Figure 8

lab number	A 5 days	B 5 days	A 6 days	B 6 days	A 7 days	B 7 days	A 8 days	B 8 days	A 12 days	B 12 days
1	0.2290	0.2180	0.2400	0.2620	0.2620	0.3050	0.2840	0.3490	0.4070	1.0250
2	0.1860	0.2950	0.2180	0.3280	0.2510	0.3600	0.2840	0.3930	0.3930	0.5350
3	0.3270	0.1530	0.3930	0.2180	0.4580	0.2620	0.5240	0.3490	0.6330	0.5020
4	0.2400	0.3500	0.2800	0.3900	0.3500	0.4100	0.5240	0.4600	0.3700	0.6100
5	0.2840	0.1960	0.2840	0.2180	0.3050	0.2400	0.3270	0.2940	0.4800	0.3710
6	0.3270		0.3490		0.4580		0.4790		0.8540	
7										
8										
9	0.0000	5.0000	6.0000	5.0000	6.0000	5.0000	6.0000	5.0000	6.0000	5.0000
10	0.2660	0.2420	0.2940	0.2930	0.3470	0.3150	0.3780	0.3670	0.5150	0.6000
11	0.0569	0.0792	0.0658	0.0748	0.0926	0.0700	0.1018	0.0649	0.1105	0.2400
12	21.4000	32.7000	22.4000	26.4000	26.7000	22.2000	26.9000	17.7000	21.5000	40.8000
13										
14	n									4.0000
15	X									0.8080
16	a-1									0.0598
17	C of V %									19.8000
18	lab marked *									1.0000

STEEL SLAG DATA

Fri, Jun 13, 1997 10:30 AM

	A 13 days	B 13 days	A 14 days	B 14 days	A 15 days	B 15 days	A 16 days	B 16 days	A 20 days	B 20 days	A 21 days	B 21 days
1	0.4360	1.1780	0.4600	1.2430	0.5240	1.3310	0.6760	1.5710	0.6380	1.6360	0.7420	1.7020
2	0.4260	0.5730	0.4580	0.6110	0.4800	0.6440	0.6030	0.8000	0.6400	0.8370	0.6760	0.8730
3	0.6780	0.5450	0.7200	0.5880	0.7630	0.6540	0.8910	0.7860	0.9380	0.8290	0.9820	0.8940
4	0.5700	0.6800	0.6100	0.7400	0.6500	0.7400	0.9200	0.9400	1.0300	1.0000	1.0300	1.0700
5	0.5450	0.4150	0.5670	0.4580	0.6110	0.4800	0.8070	0.6110	0.8730	0.6760	0.9180	0.8070
6	0.6880	0.6980	0.6980	0.4580	0.7200	0.4800	0.9380	0.6110	0.9820	0.6760	1.0250	0.8070
7												
8												
9	0.0000	5.0000	6.0000	5.0000	6.0000	5.0000	6.0000	5.0000	6.0000	5.0000	6.0000	5.0000
10	0.5590	0.6780	0.5880	0.7280	0.6250	0.7700	0.8080	0.9410	0.8600	0.9960	0.8950	1.0690
11	0.1157	0.2950	0.1086	0.3047	0.1096	0.3275	0.1289	0.3708	0.1579	0.3759	0.1513	0.3663
12	20.7000	43.5000	18.4000	41.8000	17.5000	42.5000	17.2000	37.4000	18.4000	37.7000	16.9000	34.3000
13												
14	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000	4.0000
15	0.5530	0.5530	0.6000	0.6000	0.6300	0.6300	0.6300	0.7840	0.9360	0.9360	0.9360	0.9110